

VERY HIGH ENERGY GAMMA-RAY RADIATION FROM THE STELLAR-MASS BLACK HOLE CYGNUS X-1

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ABSTRACT

We report on the results from the observations in very high energy band (VHE, $E_\gamma \geq 100$ GeV) of the black hole X-ray binary (BHB) Cygnus X-1. The observations were performed with the MAGIC telescope, for a total of 40 hours during 26 nights, spanning the period between June and November 2006. Searches for steady γ -ray signals yielded no positive result and upper limits to the integral flux ranging between 1 and 2% of the Crab nebula flux, depending on the energy, have been established. We also analyzed each observation night independently, obtaining evidence of γ -ray signals at the 4.0 standard deviations (σ) significance level (3.2σ after trial correction) for 154 minutes effective on-time (EOT) on September 24 between 20h58 and 23h41 UTC, coinciding with an X-ray flare seen by *RXTE*, *Swift* and *INTEGRAL*. A search for faster-varying signals within a night resulted in an excess with a significance of 4.9σ (4.1σ after trial correction) for 79 minutes EOT between 22h17 and 23h41 UTC. The measured excess is compatible with a point-like source at the position of Cygnus X-1, and excludes the nearby radio nebula powered by its relativistic jet. The differential energy spectrum is well fitted by an unbroken power-law described by $dN/(dA dt dE) = (2.3 \pm 0.6) \times 10^{-12} (E/1\text{TeV})^{-3.2 \pm 0.6}$. This is the first experimental evidence of VHE emission from a stellar-mass black hole, and therefore from a confirmed accreting X-ray binary.

Subject headings: acceleration of particles — binaries: general — gamma rays: observations — X-rays: individual (Cygnus X-1)

1. INTRODUCTION

Cygnus X-1 is the best established candidate for a stellar mass black-hole (BH) and one of the brightest X-ray sources in the sky (Bowyer et al. 1965). Located at a distance of 2.2 ± 0.2 kpc, it is composed of a $21 \pm 8 M_\odot$ BH turning around an O9.7 Iab companion of $40 \pm 10 M_\odot$ (Ziółkowski 2005) in a circular orbit of 5.6 days and inclination between 25° and 65° (Gies & Bolton 1986). The X-ray source is thought to be powered mainly by accretion and displays the canonical high/soft and low/hard X-ray spectral states depending on the accretion rate (Esin et al. 1998). The thermal soft component is produced by the accretion disk close to the BH, whereas hard X-rays are thought to be produced by inverse Compton scattering of soft photons by thermal electrons in a corona or at the base of a relativistic jet. The results from observations in the soft γ -ray range with COMPTEL (McConnell et al. 2002) and *INTEGRAL* (Cadolle Bel et al. 2006) strongly suggest the presence of a higher energy non-thermal component. In addition, fast episodes of flux variation by a factor between 3 and 30 have been detected at different time scales, ranging from milliseconds in the 3-30 keV band (Gierliński & Zdziarski 2003)

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to several hours in the 15-300 keV band (Golenetskii *et al.* 2003). Radio emission stays at a rather stable level during the low/hard state, except for rarely observed flares (Fender *et al.* 2006), and appears to be quenched below a detectable level during the high/soft state (Brocksopp *et al.* 1999). On the other hand, VLBA images have shown the presence of a one-sided, elongated radio structure (15 mas length) during the hard state (Stirling *et al.* 2001), indicating the presence of a highly collimated (opening angle $< 2^\circ$) relativistic ($v \geq 0.6c$) jet. Romero, Kaufman Bernado & Mirabel (2002) have suggested that Cygnus X-1 is a microblazar, where the jet axis is roughly aligned with the line of sight. The interaction of the outflow from the jet with the interstellar medium appears to produce a large-scale (~ 5 pc diameter), ring-like, radio emitting structure (Gallo *et al.* 2005), which implies that most of the energy from the system is released by a radiatively inefficient relativistic jet.

Three other binary systems have been detected so far in the VHE domain, namely PSR B1259–63 (Aharonian *et al.* 2005a), LS I+61 303 (Albert *et al.* 2006a) and LS 5039 (Aharonian *et al.* 2005b). In PSR B1259–63 the TeV emission is thought to be produced by the interaction of the relativistic wind from a young non-accreting pulsar with that of the companion star. Recent results suggest that LS I +61 303 also contains a non-accreting neutron star (Dhawan, Mioduszewski & Rupen 2006), while the situation is not yet clear in the case of LS 5039. As of now, there is no experimental evidence of VHE emission from any galactic BHXB system.

In this letter we report on the –to our knowledge– first results of observations of Cygnus X-1 in the VHE regime, performed with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope. Our results pose stringent upper limits to a steady VHE flux and include evidence of an intense, fast flaring episode occurring in coincidence with an X-ray flare. We briefly describe the observations and data analysis, derive the spatial and spectral features of the observed excess, and discuss the obtained results.

2. OBSERVATIONS AND RESULTS

The BHXB Cygnus X-1 was observed with MAGIC for a total of 46.2 hours between June and November 2006. MAGIC is an Imaging Atmospheric Cherenkov Telescope (IACT) located at La Palma (Canary Islands, Spain), at 28.8°N , 17.8°W , 2200 m.a.s.l. The telescope’s sensitivity is $\sim 2\%$ of the Crab nebula flux in 50 hours of observations. The angular resolution is $\sim 0.1^\circ$, and the energy resolution above 150 GeV is about 20%. MAGIC can provide γ -ray source localization in the sky with a precision of $\sim 2'$ and is able to observe under moderate moonlight or twilight conditions (Albert *et al.* 2007). At La Palma, Cygnus X-1 culminates at a zenith angle of 5° and the observations were carried out at zenith angles between 5° and 35° . The brightest object in the Cygnus X-1 field of view is the 3.89 magnitude, K0 spectral-type star η Cygni, located $26'$ away from Cygnus X-1. The observations were carried out in the false-source track (wobble) mode (Fomin *et al.* 1994), with two directions at $24'$ distance and opposite sides of the source direction. This technique allows for a reliable estimation of the background with no need of extra observation time. One of the tracked directions corresponds roughly to that of η Cygni, which reduces the effect of the star in the data analysis.

Data corresponding to 46.2 hours from 26 nights of observation were analyzed using the standard MAGIC calibra-

TABLE 1
CYGNUS X-1 OBSERVATION LOG^a

MJD [days]	T [min]	N_{excess} [evts]	S [σ]	Post [σ]	U.L. [evts (% CU)]
53942.051	61.1	3.6 ± 4.8	0.8	< 0.1	15.02(11.1)
53964.887	105.6	4.8 ± 6.9	0.7	< 0.1	21.49(9.2)
53965.895	195.3	-13.2 ± 10.1	-1.3	< 0.1	8.74(2.0)
53966.934	124.8	9.4 ± 9.5	1.0	< 0.1	33.07(11.9)
53967.992	48.5	-9.0 ± 4.7	-1.7	< 0.1	1.57(1.5)
53968.883	237.5	-4.4 ± 11.6	-0.4	< 0.1	22.76(4.3)
53994.953	53.6	-4.0 ± 4.9	-0.8	< 0.1	6.84(5.8)
53995.961	58.1	-2.8 ± 4.6	-0.6	< 0.1	7.76(6.0)
53996.855	176.2	1.6 ± 9.1	0.2	< 0.1	22.15(5.7)
53997.883	132.7	5.2 ± 7.6	0.7	< 0.1	22.95(7.8)
54000.852	165.2	11.4 ± 9.7	1.2	< 0.1	35.41(9.7)
54002.875	154.4	36.8 ± 10.4	4.0	3.2	...
54003.859	166.9	-7.0 ± 9.1	-0.8	< 0.1	13.35(3.6)
54004.891	123.3	-6.0 ± 7.9	-0.7	< 0.1	11.33(4.1)
54005.914	87.9	-2.2 ± 6.3	-0.3	< 0.1	11.88(6.1)
54006.938	28.0	5.4 ± 4.1	1.4	< 0.1	15.26(24.6)
54020.891	65.5	-8.6 ± 5.9	-1.4	< 0.1	4.27(2.9)
54021.887	68.6	-6.2 ± 5.7	-1.0	< 0.1	6.30(4.1)
54022.887	58.1	1.6 ± 5.9	0.3	< 0.1	14.55(11.3)
54028.863	68.6	3.4 ± 5.9	0.6	< 0.1	18.28(12.0)
54029.895	33.5	3.4 ± 5.1	0.7	< 0.1	15.93(21.5)
54030.863	19.6	-1.8 ± 3.0	-0.6	< 0.1	5.41(12.5)
54048.824	47.2	1.6 ± 5.7	0.3	< 0.1	14.99(14.3)
54049.824	47.9	-6.0 ± 5.4	-1.1	< 0.1	6.09(5.7)
54056.820	27.1	-5.2 ± 3.8	-1.3	< 0.1	3.55(5.9)
54057.820	21.5	1.2 ± 2.6	0.5	< 0.1	7.96(16.7)

^a From left to right: Modified Julian Date of the beginning of the observation, total observation EOT, number of excess events, statistical significance of the excess, equivalent (*post-trial*) significance for 26 independent samples and signal upper limit for the different observation nights. A cut $\text{SIZE} > 200$ photo-electrons ($E_\gamma > 150$ GeV) has been applied. Upper limits (Rolke, López & Conrad 2005) are 95% confidence level (CL) and are quoted in number of events and in units of the γ -ray flux measured for the Crab nebula, assuming the Crab nebula spectral slope ($\alpha = -2.6$).

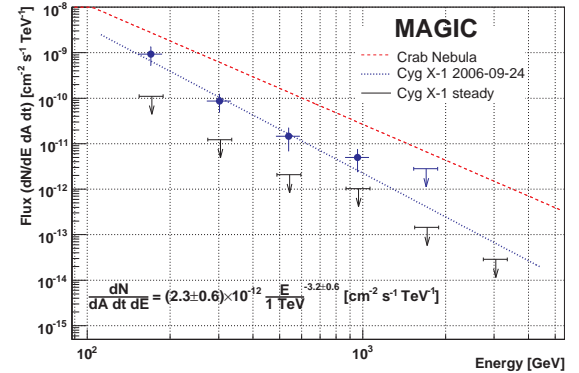


FIG. 1.— Differential energy spectrum from Cygnus X-1 corresponding to 78.9 minutes EOT between MJD 54002.928 and 54002.987 (2006-09-24). Also shown are the Crab nebula spectrum and the best fit of a power-law to the data and the 95% confidence level upper limits to the steady γ -ray flux (Rolke, López & Conrad 2005).

tion and analysis software (Albert *et al.* 2006b; Gaug *et al.* 2005). Data runs with anomalous event rates (6.2 hours) were discarded for further analysis, leading to a total of 40.0 hours of useful data (see Table 1 for details). Hillas variables (Hillas 1985) were combined into an adimensional γ /hadron discriminator (*hadronness*) and an energy estimator by means of the Random Forest classification algorithm, which takes into account the correlation between the different Hillas variables (Breiman 2001; Bock *et al.* 2005). The incoming direction of the primary γ -ray events was estimated using the DISP method, suited for observations with a single

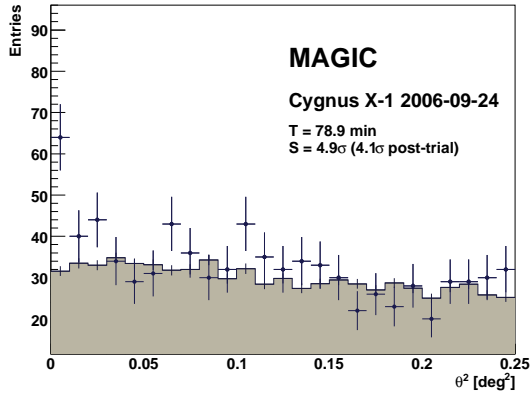


FIG. 2.— Distribution of θ^2 values for the source (dots) and background (histogram) for an energy threshold of 150 GeV.

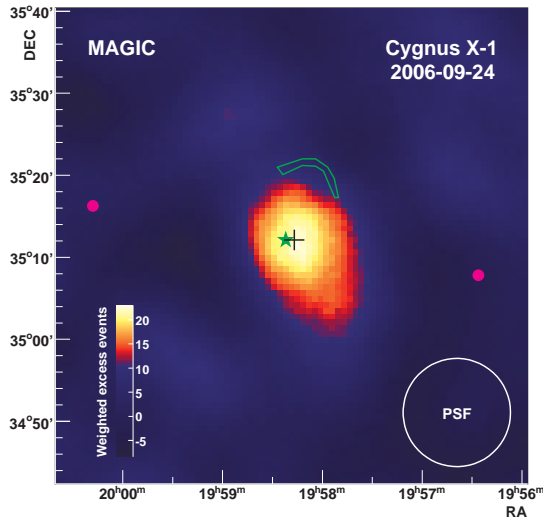


FIG. 3.— Gaussian-smoothed ($\sigma = 4'$) map of γ -ray excess events (background subtracted) above 150 GeV around Cygnus X-1 corresponding to 78.9 minutes EOT between MJD 54002.928 and 54002.987 (2006-09-24). The black cross shows the best-fit position of the γ -ray source. The position of the X-ray source and radio emitting ring-like are marked by the green star and contour, respectively. The purple dots mark the directions tracked during the observations. Note that the bin contents are correlated due to the smoothing.

IACT (Fomin et al. 1994; Domingo-Santamaría et al. 2005). These algorithms were trained with a sample of Monte Carlo (MC) simulated γ -ray events (Majumdar et al. 2005) and optimized on 3.7 hours of observations of the Crab nebula performed during the same epoch at similar zenith angles (12° – 32°), yielding the signal selection cuts $\text{hadronness} < 0.1$ and $\theta < 0.1^\circ$ (where θ is the angular distance to the source position). The residual background was evaluated from 5 circular control regions, located symmetrically to the source position with respect to the camera center. For daily searches we increase the sample for background estimation by adding control regions corresponding to close days, obtaining on average 22 times higher statistics than in the on-source region.

A search for steady γ -ray signals was performed for the entire recorded data sample, yielding no significant excess. This allows us to establish the first upper limits to the VHE γ -ray steady flux of Cygnus X-1 in the range between 150 GeV and 3 TeV (see Figure 1), of the order of 1–5% of the Crab nebula flux. Given the time scale of the variability of Cygnus X-1 at other energy bands, γ -ray signals are searched for also on a daily basis. The results are shown in Table 1. We obtain re-

sults compatible with background fluctuations at 99% CL for all the searched samples except for MJD=54002.875 (2006-09-24). We derive upper limits to the integral flux above 150 GeV between 2 and 25% of the Crab nebula flux (depending basically on the observation time) for all samples compatible with background fluctuations. The data from 2006-09-24 were further subdivided into two halves to search for fast varying signals, obtaining 0.5σ and 4.9σ effects for the first (75.5 minutes EOT starting at MJD 54002.875) and second (78.9 minutes EOT starting at MJD 54002.928) samples, respectively. The post-trial probability is conservatively estimated by assuming 52 trials (2 per observation night) and corresponds to a significance of 4.1σ . The sample corresponding to MJD 54002.928 was further subdivided into halves, obtaining 3.2σ and 3.5σ excesses in each. At this point we stopped the data split process.

The distribution of θ^2 for signal and background events corresponding to the 78.9 minutes EOT sample starting at MJD 54002.928 is shown in Figure 2. The excess is consistent with a point like source located at the position of Cygnus X-1. The map of excess events around the source is shown in Figure 3. A Gaussian fit yields the location: $\alpha = 19^{\text{h}}58^{\text{m}}17^{\text{s}}$, $\delta = 35^\circ12'8''$ with statistical and systematic uncertainties $1.5'$ and $2'$, respectively, compatible within errors with the position of Cygnus X-1 and excluding the jet-powered radio nebula at a distance of $\sim 8'$. The energy spectrum is shown in Figure 1. It is well fitted ($\chi^2/n.d.f = 0.5$) by the following power law: $dN/(dA dt dE) = (2.3 \pm 0.6) \times 10^{-12} (E/1 \text{ TeV})^{-3.2 \pm 0.6} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ where the quoted errors are statistical only. We estimate the systematic uncertainty to be 35% on the overall flux normalization and 0.2 in the determination of the spectral index.

3. DISCUSSION

The excess from the direction of Cygnus X-1 occurred simultaneously with a hard X-ray flare detected by *INTEGRAL* (~ 1.5 Crab between 20–40 keV and ~ 1.8 Crab between 40–80 keV) (Türler et al. 2006), *Swift*/BAT (~ 1.8 Crab between 15 and 50 keV) and *RXTE*/ASM (~ 0.6 Crab between 1.5 and 12 keV). Figure 4 shows the correlation between MAGIC, *Swift*/BAT and *RXTE*/ASM light-curves. The TeV excess was observed at the rising edge of the first hard X-ray peak, 1–2 hours before its maximum, while there is no clear change in soft X-rays. Additionally, the MAGIC non-detection during the following night (yielding a 95% CL upper limit corresponding to a flux ~ 5 times lower than the one observed in the second half of 2006-09-24) occurred during the decay of the second hard X-ray peak. This phenomenology leads us to think that, during the 2006-09-24 night, soft and hard X-rays are produced in different regions. Furthermore, hard X-rays and VHE γ -rays could be produced at regions linked by the collimated jet, e.g. the X-rays at the jet base and γ -rays at an interaction region between the jet and the stellar wind. These processes would have different physical timescales, thus producing a shift in time between the TeV and X-ray peaks. Note that the distance from the compact object to the TeV production region is constrained below $2'$ by MAGIC observations and therefore it is unrelated with the nearby radio emitting ring-like structure (Gallo et al. 2005). A jet scenario is, however, not devoid of constraints either. The observed TeV excess took place at phase 0.91, being 1 the moment when the BH is behind the massive star. At this phase, MAGIC observations are available only for the night 2006-09-24, which precludes any possible analysis of a putative periodicity fea-

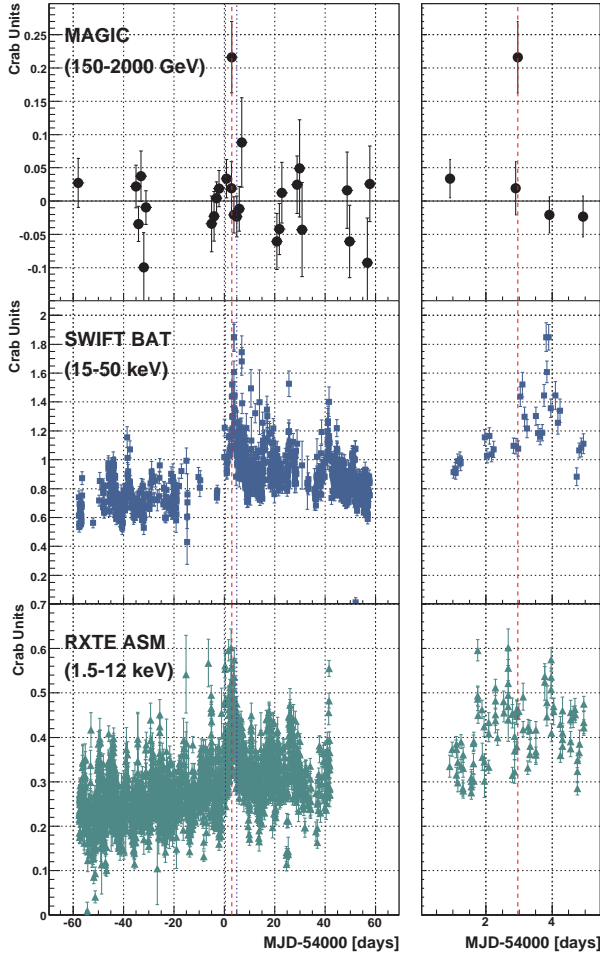


FIG. 4.— From top to bottom: MAGIC, *Swift*/BAT (from <http://swift.gsfc.nasa.gov/docs/swift/results/transients/>) and *RXTE*/ASM (from http://heasarc.gsfc.nasa.gov/xte_weather/) measured fluxes from Cygnus X-1 as a function of the time. The left panels show the whole time spanned by MAGIC observations. The vertical, dotted blue lines delimit the range zoomed in the right panels. The vertical red line marks the time of the MAGIC signal.

ture of the TeV emission. If the TeV emission were produced in the jet well within the binary system, the photon-photon absorption in the stellar photon field would be dramatic, yielding a TeV detection very unlikely. For instance, Bednarek & Giovannelli (2007) computed the opacity to pair production for different injection distances from the center of the massive star and angles of propagation, finding that photons propagating through the intense stellar field towards the observer would find in their way opacities of about 10 at 1 TeV. Admittedly, inclination of the orbit and angle of propagation to the observer can change these numbers, but not the fact that MAGIC observes the excess at the position where the expected opacity is highest. Therefore, even without an explanation for a TeV flare, we must consider that the emission could have been originated far from the compact object. Interactions of the jet with the stellar wind may lead to such a situation.

In summary, for the first time we have found experimental evidence of VHE emission produced by a Galactic stellar-mass BH. It is also the first evidence of VHE gamma-rays produced at an accreting binary system. Our results show that a possible steady VHE flux is below the present IACT's sensitivity and tight upper limits have been derived. On the other hand, we have found evidence for an intense flaring episode during the inferior conjunction of the optical star, of time scale shorter than 1 day and rising time of about 1 hour, correlated with a hard X-ray flare observed by *Swift* and *INTEGRAL*. These results point to the existence of a whole new phenomenology in the young field of VHE astrophysics of binary systems to be explored by present and future IACT's.

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